Table 1 - Comparison of Calculated Package Efficiencies of Two Standard Configurations of Phosphor Coated LED's with 3 Embodiments Disclosed in the Present Invention

LED Description	Package Efficiency		Milliwatts/lumen	
	SiC substrate	Al_2O_3 substrate	SiC substrate	Al_2O_3 substrate
1.6 mm^2 chip + 27 mm^2 reflector + phosphor on chip	58%	70%	6.7	5.6
1.6 mm^2 chip + phosphor on chip	69%	80%	5.7	4.9
1.6 mm^2 chip + 27 mm^2 reflector + phosphor on lens (fig. 5)	82%	88%	4.7	4.4
1.6 mm^2 chip + 3 mm radius hemisphere (fig. 3)	98%	99%	4	3.9
1.6 mm^2 chip + 3 mm radius sphere (fig. 4)	99%	100%	3.9	3.9

Figure 4 shows a second embodiment operating under the same principle. Here an LED chip 312 is mounted on a pedestal 314 which also serves as the heat sink. However, the chip 312 is placed at the center of a molded sphere 318. A phosphor layer (not shown) is then coated on the inside surface 320 of the sphere 318 or, alternately, intimately dispersed within the sphere. In this design the LED will radiate uniformly in all directions. Again, it is clear that both blue/UV radiation and visible radiation generated by the phosphor coating and scattered back into the sphere will be more likely to strike other phosphor coated surfaces in preference to striking either the chip 312 or the pedestal 314. These light absorbing structures are small targets for the diffuse radiation. As seen in Table 1, the package efficiency is close to 100% for this arrangement. The lower package efficiency for LED structure on SiC substrates are due to greater absorption of the LED radiation by the SiC substrate as compared to the Al_2O_3 substrate.

From the previous embodiments, It is apparent that the specific shape of the phosphor coating is not important as long as it surrounds as completely as possible the LED chip and is a distance sufficient from this chip (e.g. a distance such that the phosphor coated surface has a surface area greater than about 10 times the exposed surface area of the chip) such that radiation scattered from the coating is unlikely to strike the chip or chip structures. The invention is not limited to the embodiments described herein but intended to embrace all such coating shapes, and preferably wherein the phosphor covered surfaces has approximately 10 times the exposed area of the absorbing parts of

the LED or greater. Thus, the lens on which the phosphor is coated is not limited to hemispherical or spherical, but can include any geometric shape, preferably with the phosphor coated surface area being about at least 10 times the exposed area of the absorbing parts of the LED.

The invention is also intended to cover geometries which are not so ideal and perhaps do not give the full advantage of 100% package efficiency but nevertheless do utilize the principle of a remote phosphor coating designed so that the coated surface is at least 10 times the emitting area of the chip. For example Figure 5 shows a schematic of a conventional surface mount LED. In this arrangement, the LED chip 412 and submount 414 are mounted in a reflector cup 416. Unlike the conventional design (described in the background above), which has the phosphor embedded more or less randomly in an optical medium between reflector and the lens, the phosphor coating is applied as a layer on a transparent lens 418. The phosphor coating is remote from the chip 412 and on a surface with about >10 times the exposed area of the absorbing parts of the LED. Obviously, the surface of the lens 418 on which the phosphor coating is applied can have a surface area less than 10 times the surface area of the chip. However, the package efficiency of the assembly will be reduced accordingly, since more of the radiation will strike and be absorbed by the chip. Again, a second lens 430 can be mounted over the phosphor coated lens for protection.

Most of the UV or blue radiation and visible radiation which is scattered back from the phosphor coating strikes either the reflector cup 416 or other phosphor surface. Only a relatively small amount strikes the light absorbing chip and submount. In this design it is important that the reflector cup 416 be made of a very highly reflective material, for example a vapor deposited and protected silver coating with >95% reflectivity or an inorganic powder of high purity, such as finely divided alumina or titania. In addition the reflector cup 416 may or may not be coated with the phosphor. Table 1 shows the simulated performance of a specific LED with an area of 1.6 mm^2 on a submount in a silver reflector cup utilizing a phosphor coated lens of area of 27 mm^2.

As shown in Figures 6 and 7, the present invention also discloses the concept of a remote phosphor coating as applied to systems containing multiple LED chips. Multiple blue or UV emitting LED's can be mounted on a

single reflective electrical interconnect board or other structure. A phosphor coated surface then is used to surround not a single LED but the entire set of LED's. The phosphor coated surface may be used alone or in combination with other highly reflecting surfaces to surround the set of LED's. Two examples of such structures are shown in Figures 6 and 7. One is a power module 500 which might be used as a downlight. The other is a panel lamp 600 with many LED's mounted behind a phosphor coated panel. It is clear that many such arrangements could be made provided that the phosphor surface area is the preferred 10 times the exposed area of the absorbing parts of the LED.

As detailed above, any of the embodiments may include an epoxy or other transparent filler between the LED chip and the phosphor coated lens. More efficient extraction of light can be realized when the refractive index of the encapsulant or transparent filler is closely matching the geometric mean of the refractive indexes of the die and the lens, preferably within about 20% of this value, and even more preferably within about 10%. This reduces the amount of internal reflections in the lamp. Thus, in the case of a GaN LED chip having a refractive index of about 2.7 with a lens having a refractive index of about 1.5, the filler will preferably have a refractive index of from about 2.1. In the case of an LED chip having two or more materials having different refractive indices, such as a GaN semiconductor on a sapphire submount having a refractive index of about 1.7, the refractive index of the encapsulant will preferably match the geometric mean of the lens and the higher of the two. Better light extraction can thus be achieved with encapsulants having a higher index of refraction than epoxy, such as spin-on glass (SOG) or other high refractive index materials.

Any of the above embodiments can also be equipped with one or more band pass filters to further improve the efficiency of the resulting LED package. Thus, in one embodiment, as shown in figure 9, a lens 718 for a blue LED source is shown containing a first band pass filter 750. The band pass filter is positioned between the phosphor layer 724 and the LED (not shown). The band pass filter is selected such that the incident light from the blue LED source 752 is allowed to pass while the light emitted from the phosphor layer 754 is reflected outward.

In the embodiment shown in figure 10, two band pass filters are provided in a UV LED source package. In this embodiment, a first band pass filter 850 is positioned between the phosphor layer 824 and the LED source (not shown) adjacent a lens 818. The first band pass filter acts to transmit the UV light 852 from the LED while reflecting the light emitted from the phosphor layer 854. A second band pass filter 856 reflects the UV light from the LED 852 while allowing the light emitted from the phosphor layer 854 to pass. This arrangement prevents the transmission of potentially harmful UV radiation from the package while ensuring transmission of visible light.

As seen in figure 11, an array of micro or macro lenses 960 may be formed on the outer surface of the lens 918 in any of the above embodiments to control the emission angle, direction or intensity of the emitted radiation 952 and 954.

The calculation results shown in Table 1 are based on a linear flux model illustrated in the Figure 8. The figure shows nine fluxes incident on four surfaces of the LED package. These fluxes are described by the nine linear equations below, with each equation describing the flux with the corresponding number. The equations are:

1. $L_3^{out} = L_3^+ t_3^{VIS}$
2. $L_3^- = L_3^+ r_3^{VIS} + I_3^+ a_3^{UV} Q(\bar{\lambda}_I / \bar{\lambda}_L)(\frac{1}{2})$
3. $L_3^+ = L_2^- p_{2\,3} + L_1^- p_{1\,3} + L_0^- p_{0\,3} + I_3^+ a_3^{UV} Q(\bar{\lambda}_I / \bar{\lambda}_L)\frac{1}{2}$
4. $L_2^+ = L_3^- p_{3\,2} + L_1^- p_{1\,2} + L_0^- p_{0\,2} + I_2^+ a_2^{UV} Q(\bar{\lambda}_I / \bar{\lambda}_L)\frac{1}{2}$
5. $L_2^- = L_2^+ r_2^{VIS}$
6. $L_1^+ = L_3^- p_{31} + L_2^- p_{21} + L_0^- p_{01}$
7. $L_1^- = L_1^+ r_1^{VIS}$
8. $L_0^+ = L_3^- p_{30} + L_2^- p_{20} + L_1^- p_{10}$
9. $L_0^- = L_0^+ r_0^{VIS}$

These surfaces are:

3 = the upper phosphor coated surface,

2 = the lower phosphor coated surface,

1 = the reflector and submount, and

0= the blue or UV emitting chip.

There are nine other equations describing the blue or UV fluxes. The equations describing the blue or UV fluxes are not shown. They are coupled to the visible light equations through the quantum efficiency Q and the Stoke's shift ($\lambda i/\lambda l$). The eighteen linear equations result in eighteen unknowns, i.e. the relative powers of radiation striking each surface, and are solved simultaneously.

The p values are the probabilities that radiation from one surface will strike another. In the calculations shown in Table I these were taken to be the ratios of surface areas. Q is the quantum efficiency of the phosphor. λ is the average wavelength of the blue or UV chip radiation or the average wavelength of the visible emission of the phosphor.

The other parameters needed are the reflectivities and absorptivities of the different material surfaces. These were obtained either from Handbook values or were measured directly using known methods. There are no values for the reflectivities of the chips and so these were calculated by assuming that each chip consisted of the semiconductor layers and substrate. All radiation incident on the chip was assumed to be normal and incident on the substrate in a flip-chip design and diffraction effects were ignored. Up to second order the expression for the reflectivity of the chip is then:

$$R = R_{sub} + (1-R_{sub})^2 \exp(-2\ a_{sub}\ t_{sub})\ R_{act} + (1-R_{Sub})^2 \exp(-2\ a_{sub}\ t_{sub})\ (1-R_{act})^2 \exp(-2\ a_{act}\ t_{act})\ R_{mst} \ldots$$

where:

R_{sub} = reflectivity of substrate	R_{act} = reflectivity of active layers
a_{sub} = absorption cost of sub	a_{act} = absorption coefficient of active layers
t_{sub} = thickness of substrate	t_{act} = thickness of active layers

Known or estimated values were used for the indices of refraction, the absorption coefficients and thicknesses. Thus,

$R= ((n1-n2)^2 + k^2)/(n1+n2)^2 + k^2)$, where $k = \lambda a/2\pi$.

The invention has been described with reference to the preferred embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations.

1. An LED device comprising:

a light emitting semiconductor;

a transparent lens covering said semiconductor and spaced apart therefrom; and

a phosphor layer contained within or coated on an inside or outer surface of said lens.

2. An LED device according to claim 1, wherein said inside surface of said lens has a surface area at least ten times the exposed surface area of the light emitting semiconductor.

3. An LED device according to claim 1, further comprising a transparent filler positioned between said light emitting semiconductor and said lens.

4. An LED device according to claim 3, wherein said transparent filler is an optical coupling material which may be an epoxy, silicone, acrylic, thermoplastic, urethane, polyimide or an index modified matching fluid or gel.

5. An LED device according to claim 4, wherein said filler has an refractive index closely matching the geometric mean of the refractive index of said light emitting semiconductor and said lens material.

6. An LED device according to claim 1, wherein said phosphor layer has a substantially uniform thickness.

7. An LED device according to claim 1, wherein said phosphor layer is formed from a slurry comprising one or more phosphors and a binder.

8. An LED device according to claim 1, wherein said phosphor layer is formed from a slurry comprising one or more phosphors, a scattering medium and a binder.

9. An LED device according to claim 7, wherein said slurry may contain a carrier solvent and said binder is a transparent refractive index matching material.

10. An LED device according to claim 9, wherein said solvent is methyl ethyl ketone and said binder is selected from the group consisting of silicone, acrylic, epoxy, thermoplastic and polyimide.

11. An LED device according to claim 1, wherein said phosphor layer comprises one or more of $Y_3Al_5O_2$:Ce, $Tb_3Al_{4.9}O_{12}$:Ce, $Sr_4Al_{14}O_{25}$:Eu, and mixtures thereof.

12. An LED device according to claim 1, wherein said light emitting semiconductor is a blue emitting LED or a UV emitting LED having a primary emission in the range of 200-480 nm.

13. An LED device according to claim 1, wherein said LED device emits white light.

14. An LED device according to claim 1, having a package efficiency of 70% or greater.

15. An LED device according to claim 1, wherein said lens comprises a sphere or hemisphere and said light emitting semiconductor is positioned at the center of said sphere or hemisphere.

16. An LED device comprising:

a light emitting semiconductor;

a transparent lens covering said semiconductor and positioned apart from the light emitting semiconductor by a distance at least about two times the length of a longest side of said light emitting semiconductor; and

a phosphor layer contained within or coated on an inside or outer surface of said lens.

17. An LED device comprising

a light emitting semiconductor;

a reflector supporting said light emitting semiconductor;

a transparent lens covering said semiconductor and said reflector and spaced apart from said semiconductor; and

a uniform thickness phosphor layer coated on at least a portion of said reflector and contained within or coated on an inside or outer surface of said lens.

18. An LED device according to claim 17, further comprising a reflective layer positioned between said phosphor layer and said reflector.

19. An LED device according to claim 18, wherein said reflective layer comprises a high dielectric powder.

20. An LED device according to claim 17, further comprising a submount on which said semiconductor is mounted, wherein said submount is also coated with said phosphor layer.

21. An LED device according to claim 17, wherein said phosphor layer is from 6 to 100 μm thick.

22. An LED device according to claim 17, wherein said semiconductor is a blue or UV emitting LED in the range of 200-480 nm.

23. An LED device according to claim 17, having a package efficiency of 70% or greater.

24. An LED device according to claim 17, wherein said LED chip is free of said phosphor coating.

25. A method for forming an LED device having a lens with a uniform phosphor coating, said method comprising the steps of:

providing an LED mounted on a support;

providing a transparent lens sized to fit over or around said support;

depositing a uniform thickness phosphor coating on a surface of said lens;

assemblying said LED, mount and lens to form said LED device.

26. A method according to claim 25, wherein said step of depositing said phosphor on said lens comprises the substeps of:

forming a slurry comprising phosphor powder, a solvent and a binder;

optionally heating said lens to a temperature above room temperature;

stamping, screening, dispensing, rolling, brushing or spraying said slurry onto said lens to achieve a uniform thickness coating layer; and

curing said binder to form a permanent coating layer.

27. A method according to claim 26, wherein said slurry is sprayed onto said lens using a pressurized spray method using multiple passes.

28. A method according to claim 26, wherein said solvent is selected from the group consisting of toluene, methyl ethyl ketone, methylene chloride, and mixtures thereof.

29. A method according to claim 24, wherein said binder is selected from the group consisting of silicone, epoxy, thermoplastics, acrylics, polyimides, and mixtures thereof.

30. A method according to claim 24, wherein said phosphor coating has a thickness of about 6 to about 200 μm.

31. An LED device comprising:

a plurality of light emitting semiconductors mounted on a reflective electrical interconnect board;

a transparent lens covering said semiconductors and spaced apart from said semiconductors; and

a phosphor layer contained within or coated on an inside or outer surface of said lens.

32. An LED device according to claim 31 in which said lens has a refractive index matching a refractive index of said light emitting semiconductors for improved light extraction and chip protection

33. A LED device according to claim 31, wherein said plurality of light emitting semiconductors comprise blue LEDs, said device further comprising a band pass light filter positioned on said lens between the phosphor layer and said blue LEDs, said band pass filter functioning to pass the emission wavelength of the LEDs and reflect the emission wavelength of the phosphor layer.

34. A LED device according to claim 31, wherein said plurality of light emitting semiconductors comprise UV LEDs, said device further comprising a first band pass light filter positioned on said lens between the phosphor layer and said blue LEDs, for passing the emission wavelength of the LEDs and reflecting the emission wavelength of the phosphor layer, and a second band pass light filter positioned on an exterior surface of said lens for passing the emission wavelength of the phosphors and reflecting the emission wavelength of the LEDs.

35. A LED device according to claim 31 in which an array of micro or macro lenses is formed on the outer surface of the lens to control the emission angle, direction or intensity of the emitted radiation.

36. A LED device according to claim 31 in which the lens is easily detachable from said LED device such that additional lenses containing different phosphor mixes or amounts can be installed to easily adjust the light color temperature, CIE and CRI without changing the light emitting semiconductors.